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Full Length Article

Adaptive differential search algorithm for optimal location of distributed generation in the presence of SVC for power loss reduction in distribution system

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ABSTRACT

Optimal location and sizing of multi type of distribution generations in a distribution system is of great importance for experts and industries to achieve the desired technical-economic objectives. This paper aims to develop a new planning strategy for modern power distribution system using a flexible variant based differential search (DS) algorithm named adaptive DS. The proposed algorithm investigated for solving the optimal location and sizing of multi distributed generation (DG). The total power losses have been optimized considering the cost component of DG for real power, and the cost of energy losses. The robustness of the proposed planning strategy was validated on a two practical test system, 33-Bus and 69 Bus at normal situation and considering specific loading margin stability. The results show the importance of installing the suitable size of DG at the suitable location in the presence of SVC compensators.

1. Introduction

In recent years there has been a considerable growth on the integration of various renewable sources and multi types of flexible ac transmission systems (FACTS) in many practical power systems in the world. Technology of renewable energy based distribution generation (DG) is developing fast all over the world and largely installed by utilities in distribution systems. Many researches and recent practical project related to the integration of multi type of renewable sources in distributable systems demonstrated their efficiency and ability to improve the power quality delivered to consumer [1,2]. However, a large number of papers presented also the drawbacks of integration of DG on the reliability of power system protection coordination [3,4]. A power loss is an important technical index of power quality; the total power loss should be reduced at reasonable amount to achieve the desired technical and economical objectives [5]. The transition from the conventional systems with unidirectional power flows to the modern networks with the integration of multi type of renewable sources, and the optimal management of energy becomes a complex and vital task [6]. During the last two decades, the study and analysis of the impact of DG on power quality has been well investigated. Nowadays a large number of papers have been proposed for solving various problems related to optimal location and sizing of DG considering practical constraints using deterministic methods and metaheuristic optimization methods. An excellent review of different approaches for optimally distributed renewable generation planning was presented in References 6 and 7. In Reference 8 a selection of optimal location and size of multiple distributed generations by using Kalman filter algorithm was studied, in Reference 9 optimum placement and sizing of DGs considering average hourly variations of load is proposed, in Reference 10 a new power stability index and line losses are proposed for optimal placement and sizing of a DG, in Reference 11 a novel hybrid approach to allocate renewable energy sources in distribution system is proposed, in Reference 12 the environmental benefit of distributed generation with and without emissions trading is analyzed, in Reference 13 an efficient strategy for enhancement loading capacity of distribution system through distributed generator placement considering techno-economic benefits with load growth is presented, in Reference 14 a multiple distributed generator placement strategy in primary distribution networks for loss reduction is proposed, in Reference 15 a planning strategy based DG is proposed to improve the voltage stability margin in a distribution system, in Reference 16 the optimal size of distributed generation units is considered for power losses reduction

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and voltage stability margin enhancement with network constraints is proposed, in Reference 17 an optimal placement of dispatchable and non-dispatchable renewable DG units in distribution networks for minimizing energy loss is proposed. For more details a recent and excellent review on the impact assessment of DG and FACTS controllers in power systems is proposed in Reference 18.

Various analytical approaches have been applied for optimal sitting and sizing of multi DG for minimizing line losses in radial distribution systems [19–21]. In Reference 22 a particle swarm optimization is adapted and used for optimal size and location of multiple DGs for the minimization of power loss considering load growth, in Reference 23 a combination of genetic algorithm and particle swarm optimization for optimal DG location and sizing in distribution systems is presented, in Reference 24 a new approach based on goal programming is adapted to solving the distributed generation planning, in Reference 25 a sensitivity analysis method and PSO algorithm is adapted and applied for solving the optimal reactive power control of DGs for voltage regulation of MV distribution systems, in Reference 26 a new voltage stability index under load growth is proposed for optimal placement of DG in radial distribution systems under load growth, in Reference 27 a new backtracking search optimization algorithm is adapted to solve the optimal allocation of multi-type distributed generators, in Reference 28 a MINLP technique for optimal placement of multiple DG units in distribution systems is proposed, in Reference 29 a modified teaching–learning based optimization algorithm is proposed for optimal distributed generation location and size, in Reference 30 optimal size and sitting of multiple distributed generators in distribution system is solved using bacterial foraging optimization, in Reference 31 an efficient approach is proposed for the sitting and sizing problem of distributed generation, in Reference 32 a IPSO-Monte Carlo approach is applied for optimal distributed generation allocation and sizing, in Reference 33 a particle swarm optimization algorithm is applied for optimal location and sizing of distributed generation in coordination of DSTATCOM, in Reference 34 a multi-objective quasi-oppositional teaching–learning based optimization is proposed for optimal location of distributed generator in radial distribution systems, in Reference 35 a MOPSO approach is applied for solving the optimal multi objective placement and sizing of multiple DGs and shunt capacitor banks simultaneously considering load uncertainty. Recently a novel population based global optimization algorithm named Differential Search Algorithm (DSA) is proposed by Civicioglu [36]; the particularity and efficiency of this method is validated on many standard benchmark functions [36], and results are competitive compared to many recent metaheuristic methods. In the literature a few papers have been proposed for solving problems related to power system planning and control using DS algorithm. In Reference 37 the DSA is adapted and applied to solve the reactive power planning, and in Reference 38 the DSA is applied to solve the optimal power flow under normal and contingency situation.

The DS algorithm has few parameters to adjust which are considered as an important advantage. Experience confirmed that the robustness of any metaheuristic requires a good and flexible balance between exploration and exploitation during search process.

As well demonstrated, it is mandatory to control the reactive power transit in the electric distribution network to reduce voltage drop and consequently the power losses in transmission lines particularly at critical situations. The static Var compensator (SVC) is the first device from FACTS family which is largely installed in various practical power systems in the world. Actually, the SVC has low cost compared to other devices such as STATCOM, TCSC and UPFC. The SVC relatively has a high cost compared to bank capacitors. In modern distribution power systems, characterized by the presence of various dispersed intermittent sources, the SVC becomes very suitable to ensure flexible control of voltage especially at critical situations.

The two renewable sources considered in this paper are the wind energy and solar energy. As is well known, the energy delivered by these types of sources is intermittent. During such intermittent situations unacceptable voltage deviations can occur at specified load buses. The classical compensators based bank capacitors fail to guarantee a flexible control of voltage. As an alternative to classical compensators and to ensure a flexible control of voltages, it is mandatory to use fast dynamic controllers based shunt FACTS devices for reactive power control in modern distribution network. In the literature, few papers have been proposed for optimal location and control of multi type of DG considering the FACTS devices, in particular the SVC device. In Reference 39 a dynamic strategy based metaheuristic method is applied for optimal sizing and location of SVC devices for improvement of voltage profile in distribution network with dispersed photovoltaic and wind power plants. In Reference 40 a firefly algorithm is adapted and applied for optimal real power loss and voltage stability improvement of a large transmission network, and in Reference 41 a flower pollination optimization algorithm and power loss index have been proposed for solving the optimal sizing and locations of capacitors in radial distribution systems.

The review of the different metaheuristic methods proposed in the recent literature confirmed that there is no a standard and generalized optimization technique capable for solving with accuracy all problems related to power system planning and control. In general, the drawbacks of the majority of metaheuristic methods are related to the parameters adjustment and coordination between exploration and exploitation to achieve the desired near global solution.

In this paper a new variant method named adaptive DS is proposed to improve the solution of DG location and sizing in coordination with multi SVC device. The proposed optimization strategy is adapted and applied to find the optimal location of multi type of DG to minimize the total active power losses considering security constraints at normal condition and at critical loading condition. The performance of the proposed flexible planning strategy in terms of solution quality and convergence has been validated on two standard radial distribution system 33-Bus and 69-Bus. Fig. 1 shows the structure of the proposed planning strategy based DSA to solve various optimization problems related to the modern distribution power system considering the integration of various types of DGs and shunt FACTS devices.

The contributions of this paper can be outlined as follows:

- A new variant method based on DS is proposed for maximum power loss reduction.
- Simultaneous location and sizing of distributed generation and multi flexible shunt compensator named SVC device is implemented for the maximum loss minimization.
- The proposed strategy is capable to find a competitive solution considering load growth.
- Active power loss sensitivity (APLS) and reactive power loss sensitivity (RPLS) are two indices proposed to find the best probable location of DG.

This paper has been organized as follows:

The basic mathematical description of radial distribution systems is presented in the Section 2. An overview of system compensation based shunt FACTS devices is given in Section 3. The mathematical formulation of the optimization problem considering security constraints, the cost of DG and cost of power losses is introduced in Section 4. A brief description of the mechanism search of the DS algorithm is well presented in Section 5. The proposed

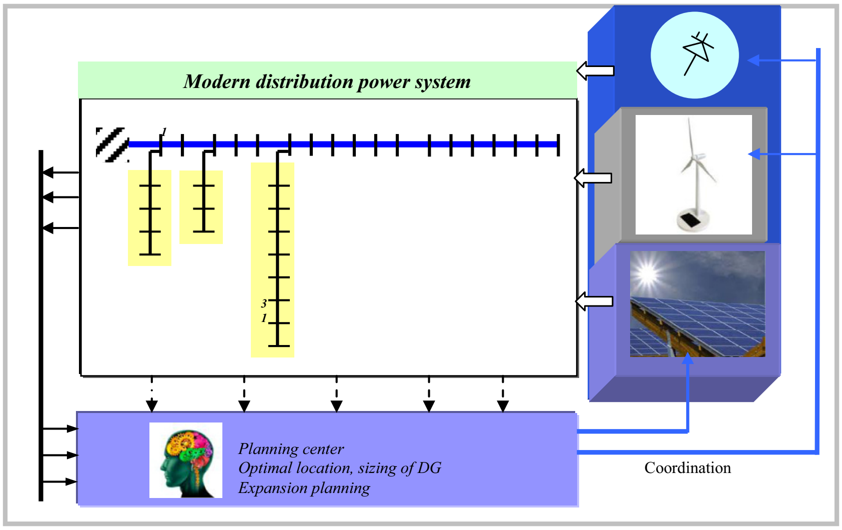

Fig. 1. Interactive structure of modern distribution power system.

variant method named adaptive DS for finding the simultaneous optimal location of DG units in coordination with SVC device is introduced in Section 6. In Section 7, the simulation results based various scenarios are presented and discussed. Finally, section 8 concludes the paper and proposes perspectives for continuation work.

2. Mathematical description of radial distribution systems

2.1. Overview

In the conventional distribution feeder (without DG units) supplied with only one source, voltage decreases toward end of the feeder, as the impedance of lines causes a voltage drop. Thus, the high voltage drop happens at the end of the feeder based on the amount of loads demand [19]. Fig. 2 shows the basic structure of a simple radial distribution (RD) with one principal feeder.

2.2. Basic equations

2.2.1. Power loss in branches

The well known generalized formulas for real and reactive power loss in the line section between buses m and $m+1$ are calculated by using the following equations:

$$P_{loss}(m, m+1) = \left(\frac{P_m^2 + Q_m^2}{|V_m|^2} \right) \cdot R_m \tag{1}$$

$$Q_{loss}(m, m+1) = \left(\frac{P_m^2 + Q_m^2}{|V_m|^2} \right) \cdot X_m \tag{2}$$

2.2.2. Total power losses

The total active and reactive power loss of the distribution system can be easily found by summing all of the branch power loss and it is expressed as:

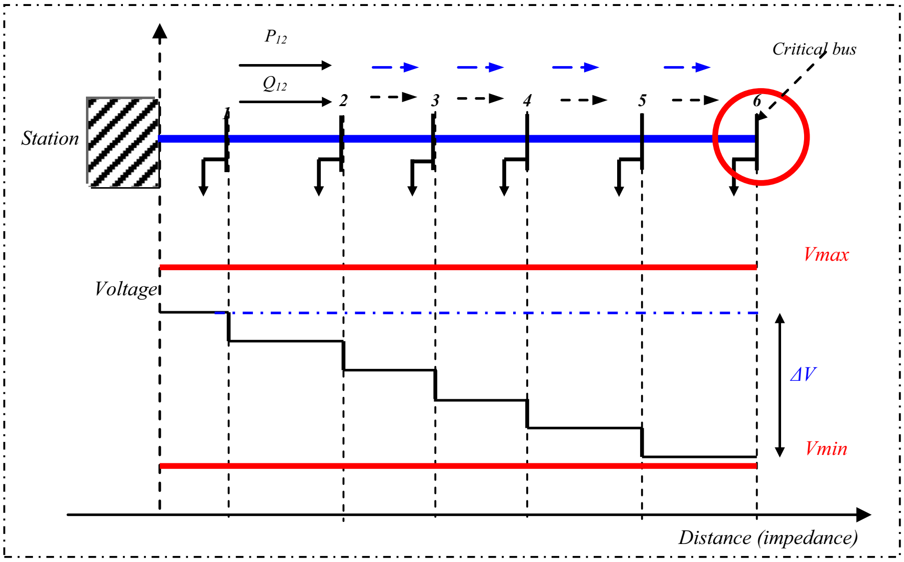

Fig. 2. Basic structure of radial distribution system.

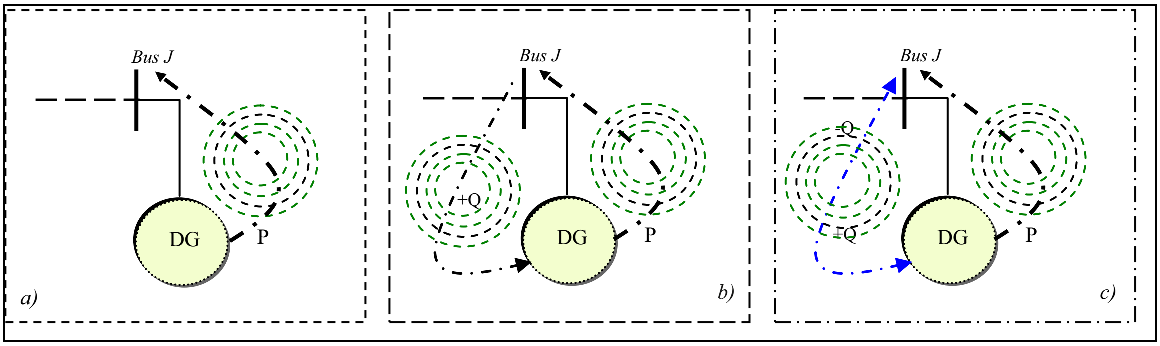

Fig. 3. Three operation mode of distributed generation: (a) DG injects active power, (b) DG injects active power and absorbs reactive power, (c) DG injects active power and absorbs or injects reactive power.

$$P_{t,loss} = \sum_{m=1}^{nbr} P_{loss}(m, m+1) \tag{3}$$

2.3. Distribution generation

In the literature many definitions have been given to introduce the distribution generation sources:

- *The Electric Power Research Institute* defines distributed generation as generation from a few kilowatts up to 50 MW [20,30].
- *The International Conference on Large High Voltage Electric Systems (CIGRE)* defines DG as smaller than 50–100 MW [20,30].
- *International Energy Agency (IEA)* defines distributed generation (DG) as generating plant serving a customer on-site or providing support to a distribution network, connected to the grid at distributed level voltages.

As well shown in Fig. 3, and based on the ability of DG resources to exchange active and reactive power with the network, the DG are classified into three categories [20,30]: (i) *DG injects active power (P) only*, (ii) *DG injects active power (P) but absorbs reactive power*, (iii) *DG injects both active (P) and absorbs or injects reactive (Q) power to the network*. As well shown in Fig. 4, with the presence of DG, if its power exceeds the local demand of loads, the power flow direction will be inversed and a voltage rise will appear at the DG connected bus.

3. System compensation based shunt FACTS devices

The Static VAr Compensator (SVC) [13] is a shunt connected VAR compensator. As well illustrated in Fig. 5(a), the structure of SVC device is simple and consists of connected anti-parallel Thyristors to provide controllability. Air core reactors and high voltage AC capacitors are the reactive power elements used together with the Thyristor valves. The SVC device has the ability to exchange in real time reactive power (absorb or generate) with the network to control voltage at specified buses of the electric power system. Fig. 5(b) shows the SVC device steady-state circuit representation.

The SVC model used in this study is based on representing the shunt Controller as variable susceptance, and the following equations describe the SVC model.

$$I_{SVC} = jB_{SVC}V \tag{4}$$

The reactive power Q_i^{SVC} exchanged with the bus i can be expressed as:

$$Q_i^{SVC} = B_i^{SVC} \cdot V_i^2 \tag{5}$$

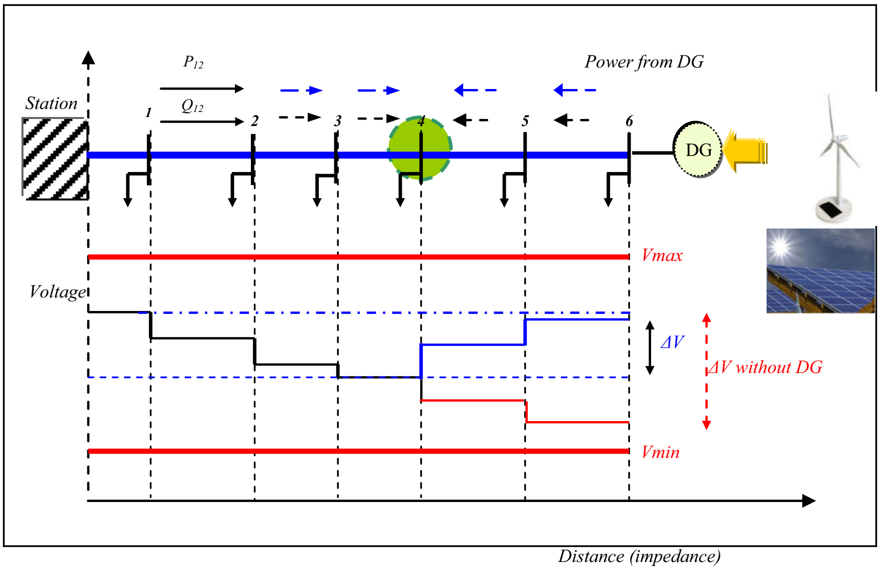

Fig. 4. Modified structure of radial distribution system considering the integration of DG.

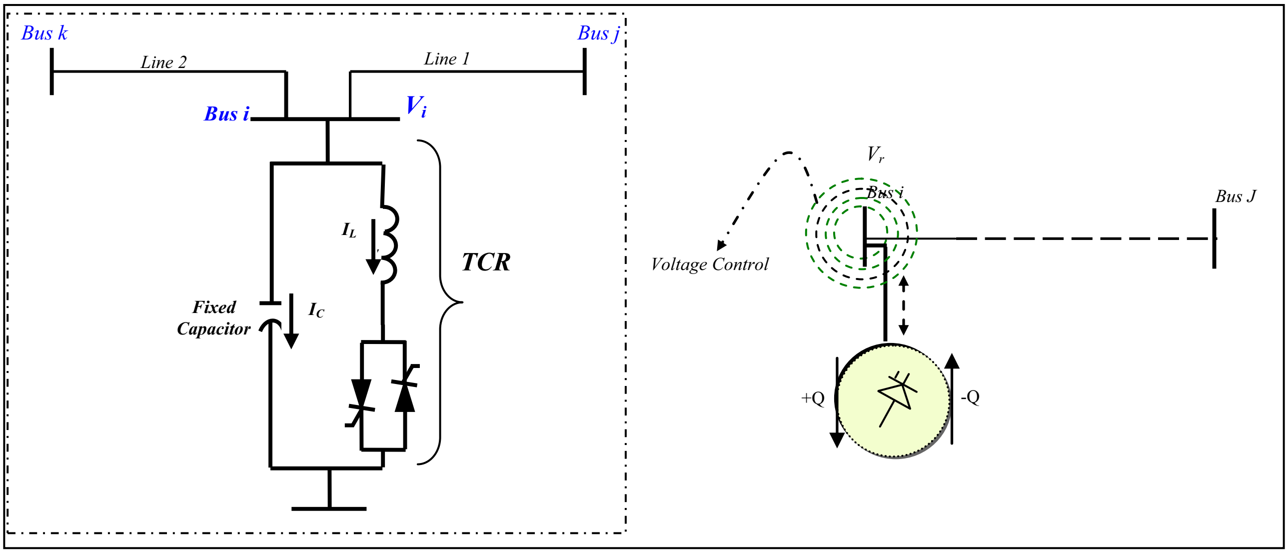

Fig. 5. (a) Basic circuit of Static Var Compensator (SVC), (b) SVC steady-state circuit representation.

3.1. *Voltage control using SVC*

The main task of installing SVC device in practical distribution systems is to control the voltage at critical bus by dynamically exchanging the reactive power with the network. Fig. 6 shows the basic principle of voltage control in simple radial distribution power system using SVC device.

The voltage drop between bus *i* and bus *j* is expressed as:

- *Before reactive compensation*

$$\Delta U_{12} = \frac{P_{12}\times R_{12} + Q_{12}\times X_{12}}{U1} \tag{6}$$

- *After reactive power compensation*

$$\Delta U_{12}^{c} = \frac{P_{12}\times R_{12} + Q_{12}^{c}\times X_{12}}{U1} = \frac{P_{12}\times R_{12} + (Q_{12} - Q_{SVC})\times X_{12}}{U1} \tag{7}$$

$$\Delta U_{12}^{c} = \frac{P_{12}\times R_{12} + Q_{12}\times X_{12}}{U1} - \frac{Q_{SVC}\times X_{12}}{U1} = \Delta U_{12} - \Delta U_{c} \tag{8}$$

where

$\Delta U_c = \frac{Q_{SVC}\times X_{12}}{U1}$ is the corrected voltage generated by SVC device.

The shunt compensation is very efficient for voltage control; consequently the amount of power losses reduced depends on the optimal location and the optimal value of reactive power to be exchanged with the network.

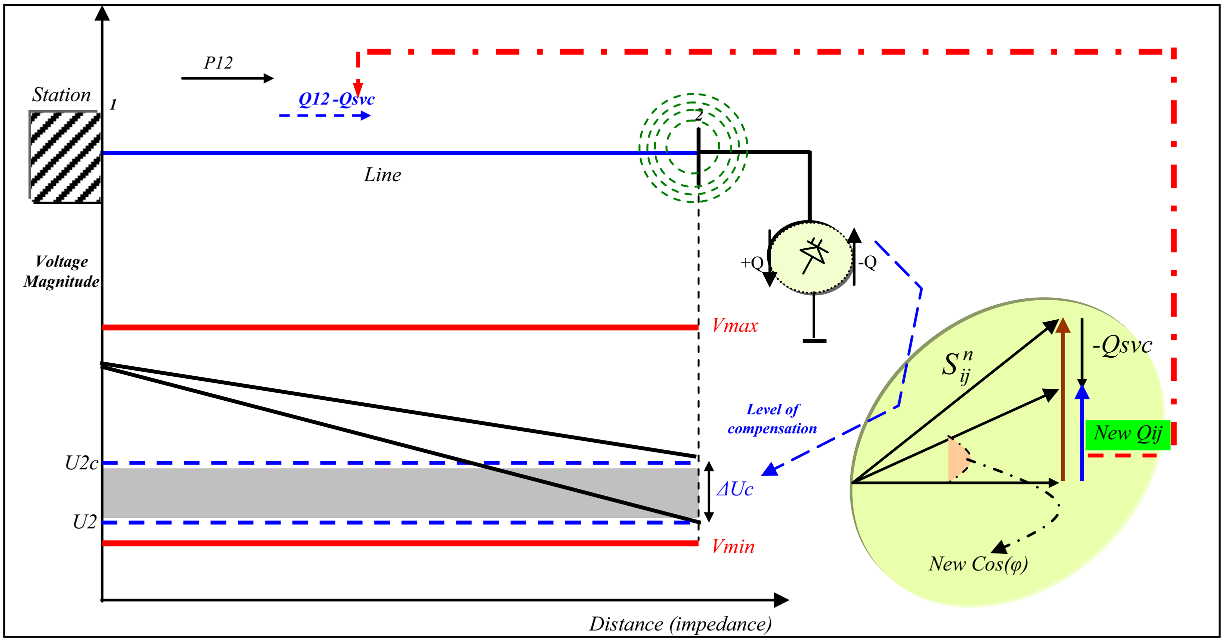

Fig. 6. Principle of voltage control using shunt compensator based SVC.

4. Problem formulation

The main objective of the proposed optimal planning strategy is to optimize the locations and the sizes of multi distributed generation and SVC device to reduce the total power loss at normal and at critical situations. The objective functions adopted in this study are reduction of active power losses, and minimization of total combined cost considering all security constraints.

4.1. Objective functions

In this study, two objective functions are considered: the total power losses and the total voltage deviation; these two objective functions are optimized considering the cost of DG installation and the cost of energy losses.

4.2. Minimization of total power loss

$$f_{loss} = Min\left(P_{t,loss} = \sum_{m=1}^{nbr} P_{loss}(m, m+1)\right) \tag{9}$$

The associated cost of energy loss and the annual cost of energy loss are expressed as follows [20]:

- Cost of energy loss

The annual cost of energy loss is given by:

$$C_{ploss} = P_{t,loss} \cdot (E_c \cdot T) \quad \$ \tag{10}$$

E_c: Energy rate (\$/kWh)
T: Time duration (h)

where $E_c = 0.06\,\$/KWh,\ T = 8760\,h$

- *Cost of DG for active power generation*

The cost characteristic of DG is formulated in a quadratic form and expressed by the following equation [20]:

$$C_{Pdg} = a \cdot P_{dg}^2 + b \cdot P_{dg} + c\ \$/h \tag{11}$$

Cost coefficients are taken as: *a = 0, b = 20, c = 0.25.*

4.3. Minimization of total combined cost

Based on Reference 41, a combined objective function is proposed to minimize the total cost which is formulated by the following combined equation:

$$Cost = K_p \times ploss \times T + K_l \times CB + K_C \times \sum_{i}^{CB} Q_{Ci} \tag{12}$$

where the constants are taken from Reference 41; these constants are identified and taken as follows:

K_p : is the cost per kWh, $K_p = 0.06\,\$/\text{kWh}$, K_C: is the cost per kVAr, $K_C = 3\,\$/\text{kVAr}$, K_l: is the cost per installation, $K_l = 1000\,\$$ and CB: is the number of compensated buses.

4.4. Constraints

4.4.1. Equality constraints

The basic active and reactive power balancing constraint is expressed by the two following expressions:

$$P_{g,slack} + \sum_{i=1}^{Ndg} P_{dg,i} = \sum_{i=1}^{Nl} P_{D,i} + \sum_{m=1}^{nbr} P_{loss,m} \tag{13}$$

$$Q_{g,slack} + \sum_{i=1}^{Ndg} Q_{dg,i} = \sum_{i=1}^{Nl} Q_{D,i} + \sum_{m=1}^{nbr} Q_{loss,m} \tag{14}$$

4.4.2. Inequality constraints

The inequality constraints represent the security constraints related to the elements of the distribution systems.

4.4.3. Voltage constraint

The following expression represents the limits on voltage magnitudes at all buses.

$$V_i^{min} \le V_i \le V_i^{max}, \quad i = 1, 2, \ldots, Nbus \tag{15}$$

- *DG constraints:*

The DG source used must be allowable in the range of size and power factor

$$P_{dg,i}^{min} \le P_{dg,i} \le P_{dg,i}^{max}, \quad i = 1, 2, \ldots, Ndg \tag{16}$$

$$Q_{dg,i}^{min} \le Q_{dg,i} \le Q_{dg,i}^{max}, \quad i = 1, 2, \ldots, Ndg \tag{17}$$

- *Maximum level of DG penetration*

The amount of power injected in the network by the DG sources compared with the total load demands of the system is called level of penetration of DG [21]. Generally, the constraint related to the penetration level is calculated as follows:

$$\sum_{i=1}^{Ndg} P_{dg,i} \le \mu \sum_{j=1}^{Nl} P_{D,j} \tag{18}$$

where μ is the penetration level.

- *SVC constraints: parameters of SVC* device *must be restricted within their limits, expressed as follows*

$$Q_{svc,i}^{min} \le Q_{svc,i} \le Q_{svc,i}^{max} \tag{19}$$

- *Branch flow:*

All the branch apparent power flows would be maintained below their thermal.

$$S_i \le S_i^{max} \quad i = 1 \ldots .. Nbr \tag{20}$$

5. Differential search algorithm

Differential Search Algorithm (DSA) is a novel population based global optimization algorithm. The behavior of DS simulates the Brownian-like random-walk movement used by an organism to migrate. The nature is the ideal source of foods for all creatures, but due to the periodical climatic changes during the year, foods vary in quantity and quality from season to season and from region to others. For this reason, many species of the living beings practice seasonal migration throughout the year and move from poor region to suitable and efficient habitat where capacity and diversity of natural sources are high. The migrating species of living beings constitute a super organism containing large number of individuals [31–33].

5.1. Mechanism search of DSA

The following stages summarize the particular methodology of search space of DSA compared to other metaheuristic methods:

- Like many stochastic optimization methods, DS algorithm, made up of random solutions of the respective problem corresponds to an artificial-super organism migrating to global optimum solution of the problem.
- Then the super organism starts to change its position by moving toward more fruitful areas.
- The mechanism search of a super organism can be described by a Brownian-like random-walk model [31].
- During search process the artificial-super organism tested whether some randomly selected positions are suitable for a temporary basis.
- If the positions tested are suitable to stop over temporarily during migration, the number of artificial super organisms that made the discovery immediately settle at the discovered position and continue their migration from this position.
- Compared to many computational-intelligence algorithms, DSA has only two control parameters to be adjusted during search process. These two parameters are: P1 and P2 which are normally set to 0.3* rand to achieve the best solutions. The DSA method has recently been used and tested with success for solving different well-known benchmark functions [31].

6. Proposed planning strategy

This section describes our contribution related to the adaptation of DS algorithm for solving the optimal location and control of multi distributed generation in coordination with SVC device.

6.1. Generate initial database

In the first stage a generalized database is obtained based on the following steps:

1.1. Run distribution power flow, determine all state variables and control variables such as: voltages at all buses, active and reactive power flow in branches, critical buses with low voltages, reactive power of slack generator and total power losses.
1.2. Select all buses with low voltage magnitude.

6.2. Location of DG

In this study and in order to reduce the search space to determine the optimal location of DG, active power loss sensitivity (APLS) and reactive power loss sensitivity (RPLS) are proposed. The APLS and RPLS values are sorted in descending order for all the branches, and the buses which have the highest value have more chances to be selected for initial candidate location to install DG; these two proposed loss sensibility are determined from Eqs (2, 1) and mathematically expressed as follows:

$$\frac{\partial P_{loss}(m,n)}{\partial Q_m} = \frac{2Q_{m+1} \cdot R_{m,m+1}}{|V_{m+1}|^2} \tag{21}$$

$$\frac{\partial Q_{loss}(m,n)}{\partial Q_m} = \frac{2Q_{m+1} \cdot X_{m,m+1}}{|V_{m+1}|^2} \tag{22}$$

6.3. Initial candidate locations

- Select the principal list containing the buses with the highest loss sensitivity.
- Select second complementary candidate buses; these buses are determined as follows: at each highest candidate buses include nearest buses (left to right) with high index.
- Locate DG at all candidate buses with the 50 and 100 of maximum power, run power flow, and sort candidate buses corresponding to the minimum power losses.

6.4. Self-adaptive DS parameters during search process

As is well known, like many metaheuristic methods, the choice of control parameters is an important task to prevent algorithm from premature convergence. The main objective of this stage is to enhance the global solution. An interactive process based on two decomposed differential search algorithm is proposed to locate the best search space. Experience confirmed that the worst solution corresponding to a specified search space may be exploited to identify new feasible regions. The value of the two parameters *P1* and *P2* suggested by authors to be normally set to ***0.3*rand*** to achieve the best solutions is not always true; our practical experience confirmed that these values depend on the particularity and complexity of the problem to be solved. For this pertinent conclusion the value of these two control parameters are dynamically adjusted during search process and updated from trail to another to ensure diversity and good balance between exploration and exploitation to achieve the near global solution.

The search space is updated by adjusting dynamically the two parameters *P1* and *P2* during search process (iterations) based on the evolution of fitness function and from trail to trail. The proposed procedure ensures the improvement of final solution by enhancing exploitation and exploration capability of the algorithm during search process. Fig. 7 shows the basic suggested self-adaptive DS parameters during search process.

7. Case studies and numerical results

7.1. Test system 1: 33-Bus

This network has a voltage of 12.66 kV, load demand of 3.715 MW and 2.300 MVAR and consists of 32 line and 33 buses. The one line diagram of the standard 33-Bus radial distribution feeder system is shown in Fig. 8: the limits of active power of DGs are between 0 and 5 MW, the maximum penetration level (μ) of DG power is constrained such that it should not exceed the total load, two penetration levels are considered ($\mu \leq 70\%$ and $\mu \leq 50\%$). In this study four scenarios are considered:

Scenario 1: Power loss optimization without considering SVC with penetration level >50%. For this first scenario two cases are examined:

Case 1: DG can exchange reactive power with the network. In this first case, and in order to show the impact of the number of DG, two tests are considered:

Case 1.1: Integration of two DG

Case 1.2: Integration of one DG

Case 2: DG cannot exchange reactive power with the network; also for this second case, two tests are performed:

Case 2.1: Integration of two DG

Case 2.2: Integration of one DG

Scenario 2: Power loss optimization considering SVC; for this second scenario two cases are examined:

Case 3: Integration of one DG with and without reactive power support considering SVC device:

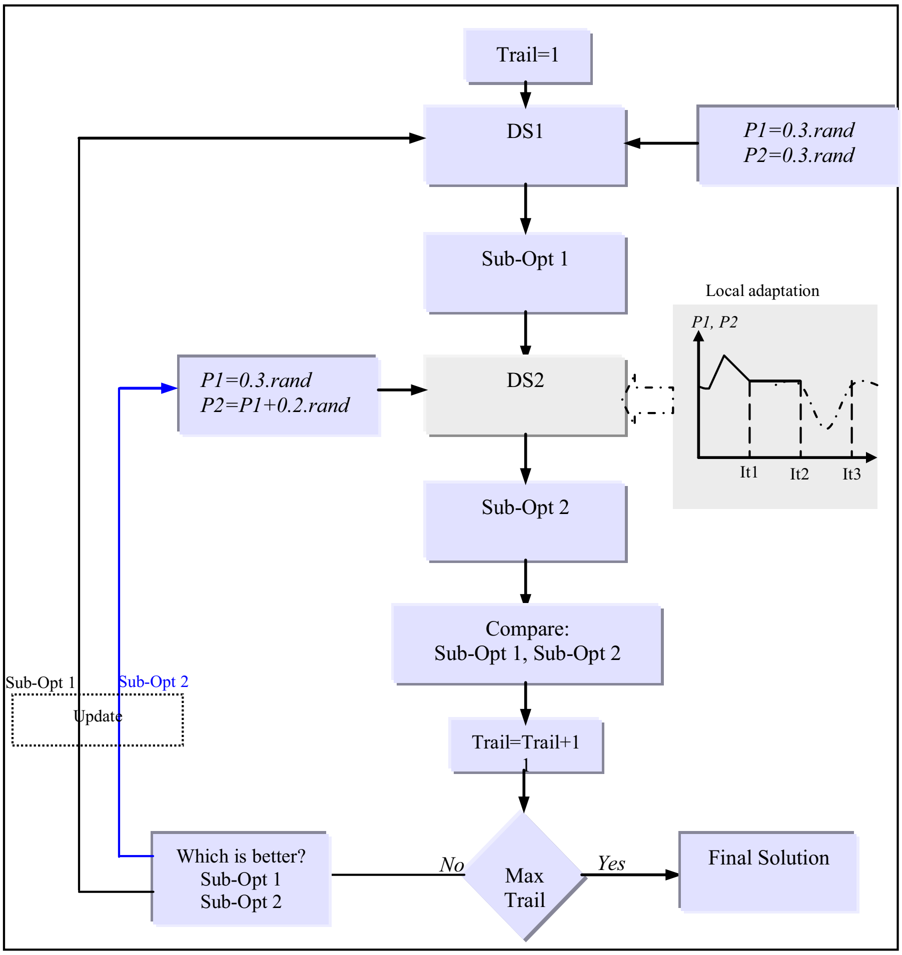

Fig. 7. Self-adaptive DS parameters during search process.

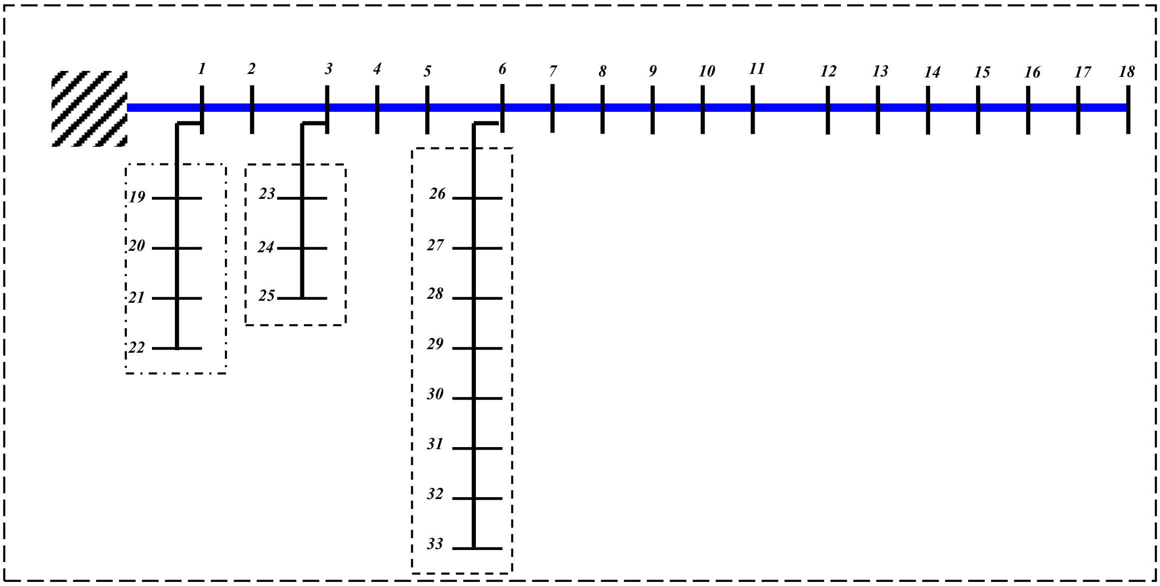

Fig. 8. Single line diagram of 33 Bus electric distribution system.

Table 1
Results for 33-Bus: integration of two DG without SVC compensation.

	Without DG	Case1: With two DG **without** reactive power support: **Case 1.1**	Case 2: With two DG **with** reactive power support: **Case 2.1**
DG location	–	**13, 30**	**13, 30**
DG size (KVA)	–	850.0816–1154.2809	845.884–1114.82
Total active power loss (KW)	202.67179	**85.908**	**28.523**
Minimum bus voltage (p.u.)	0.9130, bus 18	0.9688, bus 33	0.98018, bus 25
Pload (kW)	3715	3715	3715
Qload (KVAR)	2300	2300	2300
Cost of PDG ($/h)	0	40.75913	39.7142
Cost of energy losses ($)	106524.2961	45153.7523	**14992.076214**
Loss reduction %		**57.612%**	**85.926%**
Savings in cost of energy losses ($)	–	**61370.5438**	**91532.219886**
Total size of DG (MW)		**2.0044**	**1.9607**

Values in bold indicate the best location, sizing and fitness achieved using the proposed approach.

Scenario 3: Power loss optimization with integration of two DG with penetration level <50%, and without considering SVC device. For this scenario, two tests have been performed with and without the reactive power capability of DG.

Scenario 4: Power loss optimization with integration of two DG with penetration level >50% considering critical load growth. In this scenario, the contribution of SVC device is not considered. Two cases have been performed:

Case 4: *Integration of two DG without reactive power capability*

Case 5: *Integration of two DG with reactive power capability*

7.2. Scenario 1: Optimization without considering SVC device with penetration level >50%

The main objective of this case is to investigate the impact of DG on power loss reduction when DG can exchange reactive power with network.

7.2.1. Case 1: DG can exchange reactive power with the network

7.2.1.1. Case 1.1: Integration of two DG. For this first case study, two candidate buses are selected based on practical steps proposed within the planning strategy for optimal location of two DG to minimize the total active power loss. For this case the shunt compensations are not considered. The optimized total active power losses achieved is **28.5** KW. Active and reactive power delivered from the substation is 1790 kW and 880 KVAR respectively. The optimal sizes of active power of the two DGs are given in Table 1. Fig. 9 shows the reactive loss sensitivity index, as we can see the best candidate buses are identified. Fig. 10 shows the convergence characteristic of the power loss minimization related to the optimal DG location. In order to show the particularity and efficiency of the proposed planning strategy, results are compared to the results of many recent techniques proposed in the literature.

Table 4 shows a comparative study with other techniques treating the same problem. The distribution of voltages profile at all buses at normal condition and considering the integration of these two DG is shown in Fig. 11, which shows clearly that the voltages are improved compared to the base case.

7.2.1.2. Case 1.2: Integration of one DG. For this test, only one candidate DG is integrated at efficient location based on sensitivity index. The best candidate location is at bus 6, and the total active power is optimized with the capability of DG to exchange reactive power with the network. The optimized total active power losses achieved is **61.458** KW. The optimal size of active power of the DG is **2.47333** MW as shown in Table 2. The distribution of voltage profiles at all loads is shown in Fig. 11; as we can see the deviation of voltage is increased compared to the case considering two distributed generation. As shown, the total power loss achieved by integrating one DG is higher compared to the case considering the integration of two DG.

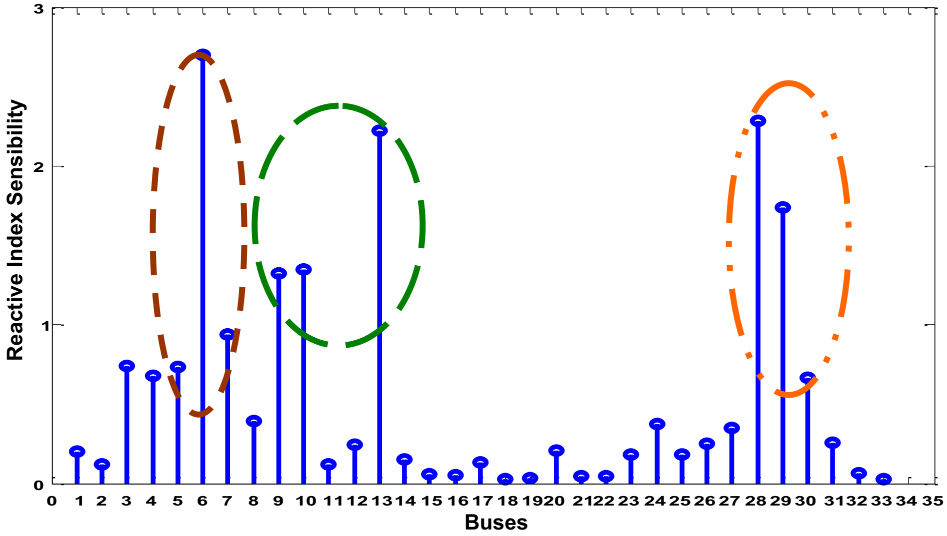

Fig. 9. Reactive loss sensitivity index.

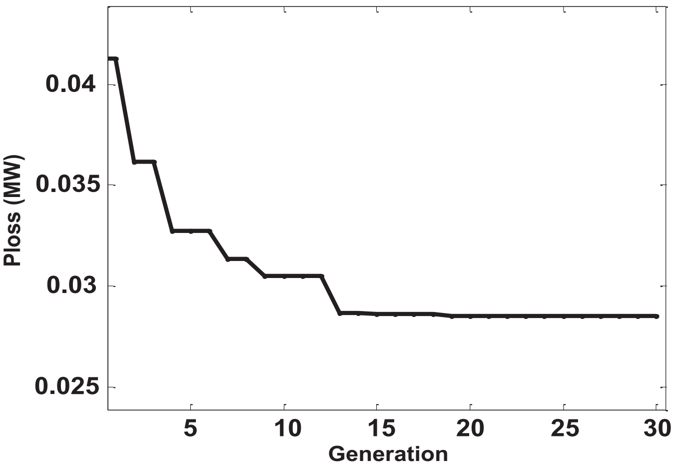

Fig. 10. Convergence characteristic for the power loss minimization: scenario 1: case 1: integration of two DG.

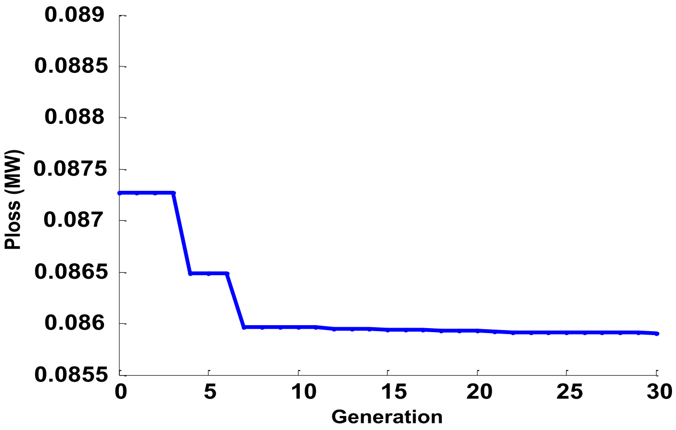

Fig. 12. Convergence characteristic of the power loss minimization: scenario 1: case 2: integration of two DG.

7.2.2. *Case 2: DG cannot exchange reactive power with the network*

7.2.2.1. Case 2.1: Integration of two DG. For this second study, the total power loss is optimized without considering the reactive power of the DG located at bus 6. The best total power loss achieved is **85.908** KW, which is higher compared to the first case. This clearly proves the importance of controlling the reactive power in coordination with active power of DG. The final convergence characteristic corresponding to power loss minimization is shown in Fig. 12. The distribution of voltage profiles at all loads is shown in Fig. 11, which shows the deviation of voltage is increased compared to the case considering the reactive power support of DG.

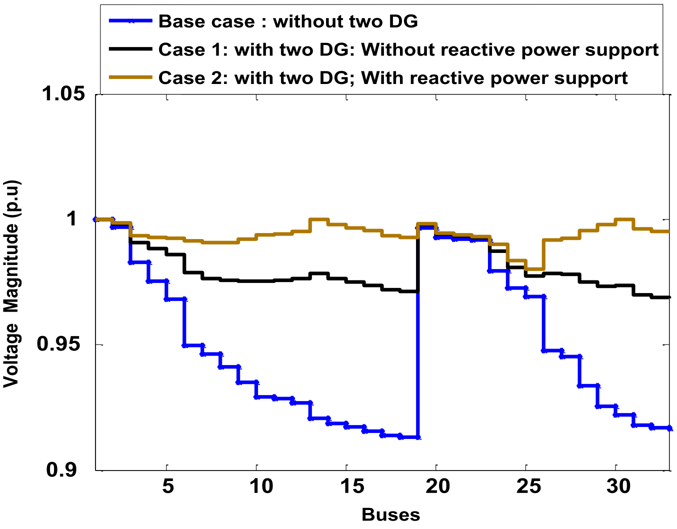

Fig. 11. Comparison of voltage profiles: cases: basic case, case 2 and case 3: (*without SVC*).

7.2.2.2. Case 2.2: Integration of one DG. For this study one DG is integrated at bus 6, the total power loss is optimized without considering the reactive power of the DG. The best total power loss achieved is **103.9638** KW, which is higher compared to the case considering the reactive power support. The distribution of voltage profiles at all loads is shown in Fig. 13; also for this case the deviation of voltage is increased compared to the case considering reactive power control of DG. This clearly proves the importance of controlling the reactive power in coordination with active power of DG. Figs. 14 and 15 show the variation of active power losses with the size of DG with and without reactive power capability.

7.3. *Scenario 2: Optimization considering SVC device*

The main objective of this scenario is to demonstrate the relation between three control variables: the active power of DG, the reactive power of DG and the reactive power of dynamic shunt compensator installed at optimal location. For this scenario the following case is considered.

Table 2
Results for 33-Bus: integration of one DG without SVC compensation.

	Without DG	With one DG without reactive power support: **Case 2.2**	With one DG with reactive power support: **Case 1.2**
DG location	–	**06**	**06**
DG size (MW)	–	2.5753	2.47333
Total active power loss (KW)	202.67179	**103.9638**	**61.458**
Minimum bus voltage (p.u.)	0.9130, bus 18	0.951 bus 18	0.96538 bus 18
Pload (kW)	3715	3715	3715
Qload (KVAr)	2300	2300	2300
Cost of PDG ($/h)	0	51.7565	49.71666
Cost of energy losses ($)	106524.2961	54643.3765	32302.41954
Loss reduction %	–	48.703%	69.676%
Savings in cost of energy losses ($)	–	**51880.9196**	**74221.87656**
Total size of DG (MW)		**2.5753**	**2.47333**

Values in bold indicate the best location, sizing and fitness achieved using the proposed approach.

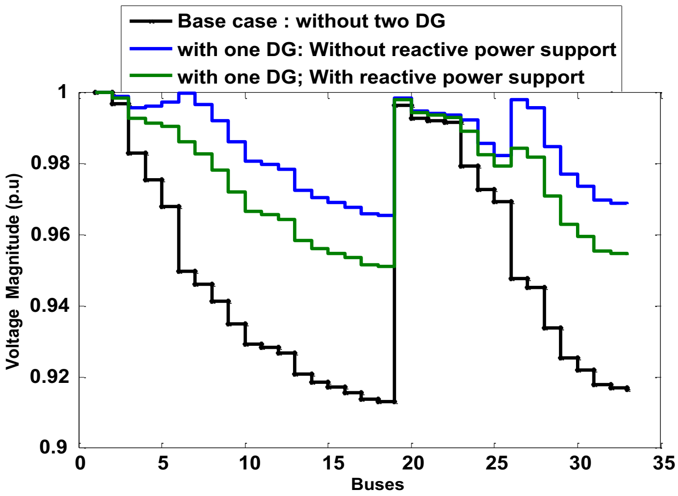

Fig. 13. Voltage profiles comparison: cases: basic case, integration of one DG with and without reactive power support of DG (without SVC).

7.3.1. Case 3: Integration of one DG with and without reactive power support considering SVC device

For this special case, only one DG is integrated in bus 6. Also one SVC is located at bus 30, the three control variables which are active and reactive power of DG, the reactive power of SVC are optimized in coordination. Table 3 shows the optimized variables achieved. The best total power loss achieved is **56.8793** MW; this value is obtained without reactive power support from DG ($\cos(\varphi) = 1$). The reactive power injected by SVC at bus 30 is 1150 KVAR. It is important to clarify that by installing SVC at efficient location, the total power loss is reduced compared to same case with one DG.

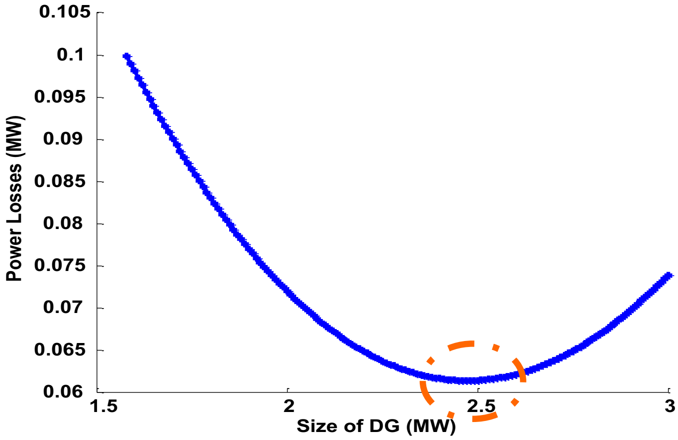

Fig. 14. Variation of active power losses with the size of DG: with reactive power capability.

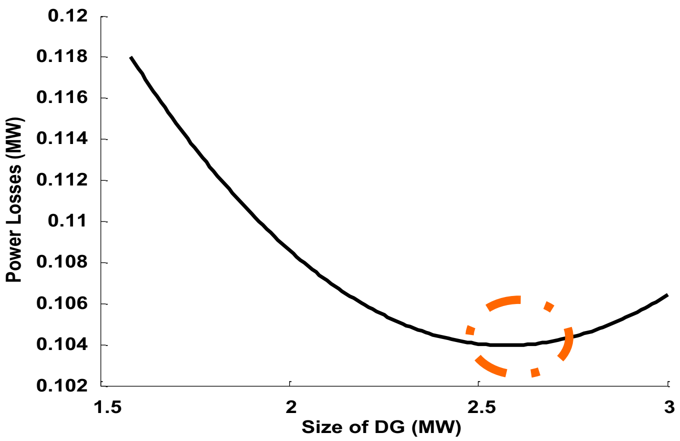

Fig. 15. Variation of active power losses with the size of DG: without reactive power capability.

7.4. Results discussions and comparative study

In order to validate the efficiency of the proposed method, in this section a technical and economic comparative study is presented to show the importance and the impact in integrating different types of DG. The integration of two DG with only active power control results in reducing total loss and consequently the cost of energy loss is reduced from $**106524.2961**, to $**45153.7523**, resulting to annual savings of $**61370.5438**. However when considering the second type of DG with reactive power control capability, the total active power loss reduced significantly. For this case the cost of energy loss is reduced to $**14992.076214**; the annual savings is $**91532.219886**. Thus, in practical issue, it is necessary to consider the reactive power available from DG to be dynamically controlled in coordination with the active power generated to exploit efficiently the DG integration by reducing the total power losses and total voltage deviation. In order to validate the efficiency of the proposed planning strategy, the best results are compared to many recent optimization techniques. As well depicted in Tables 4–7, it

Table 3
Results for 33-Bus: integration of one DG with SVC: penetration level $\mu > 50\%$.

	Without DG	With one DG **without** reactive power support	With one DG **with** reactive power support
DG location	–	**06**	**06**
DG size (MW)	–	2.94757	2.4778
Total active power loss (KW)	202.67179	**56.8793**	66.084
Minimum bus voltage (p.u.)	0.9130, bus 18	0.970 bus 18	0.965 bus 18
Pload (kW)	3715	3715	3715
Qload (KVAR)	2300	2300	2300
Cost of PDG ($/h)	0	59.2014	49.8075
Cost of energy losses ($)	106524.2961	**29895.7891**	34734.0113
Loss reduction %	–	**71.935%**	67.393%
Savings in cost of energy losses ($)	–	**76628.507**	71790.28480
Total size of DG (MW)		2.94757	2.4778
Reactive power of SVC (KVAR)		**1550**	1940
Location of SVC device		**30**	30

Values in bold indicate the best location, sizing and fitness achieved using the proposed approach.

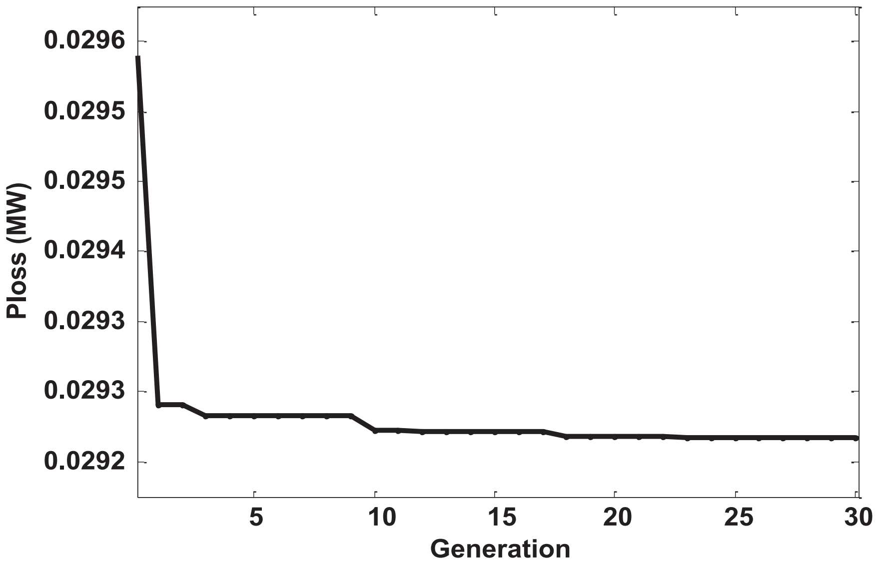

Fig. 16. Convergence characteristic of power loss minimization: two DG with reactive power support: penetration level $\mu \le 50\%$.

is observed that the optimal size of DGs obtained by the proposed approach is significantly small as compared to other methods with great increase in the percentage of power loss reduction. It is clear to conclude that the proposed planning strategy offers the best solutions and is very suitable for solving large distribution power systems considering critical situations.

Scenario 3: Optimization with integration of two DG with penetration level <50%, without considering SVC device. For this scenario, two tests were performed with and without the reactive power capability of DG.

In the recent literature, some authors validated their planning strategies on many practical distribution test systems considering a specific penetration level of DG to maintain the quality of the network; the penetration level μ cannot exceed 50% of the total power demand. In order to validate the robustness and efficiency of the proposed planning strategy, we have considered the same penetration level as suggested in Reference 21. The convergence characteristics for power loss minimization corresponding to the integration of two DG with and without reactive power support are shown in Figs. 16 and 17. The optimized total power losses based on the integration of two DGs are depicted in Tables 8 and 9. The optimal distribution of voltage magnitudes at all buses for three cases are presented in Fig. 18. It is clear that the proposed planning strategy gives better results in terms of solution quality and convergence characteristics considering different penetration levels compared to other recent proposed techniques.

Scenario 4: The main objective of this scenario is to validate the efficiency of the proposed planning strategy considering critical load

Table 4
The results of optimal DG for 33-bus compared with other algorithms. One DG without reactive power support: penetration level $\mu > 50\%$.

Methods [22]	Bus *N*	DG size (KW)	Losses (KW)	Loss reduction %
ELF	6	2600.0	111.10	47.39
IA	6	2600.0	111.10	47.39
MINLP	6	2590.0	111.01	47.39
PSO	6	2590.0	111.10	47.39
Proposed method	6	**2575.3**	**103.9638**	**48.703**

Values in bold indicate the best location, sizing and fitness achieved using the proposed approach.

Table 5
The results of optimal DG for 33-bus compared with other algorithms. One DG with reactive power support: $\mu > 50\%$.

Methods [22]	Bus *N*	DG size (KW)	Losses (KW)	Loss reduction %
IA	6	2637.00	68.157	67.69
MINLP	6	2558.00	67.854	67.84
PSO	6	2557.00	67.857	67.84
Proposed method	6	**2473.33**	**61.458**	**69.676**

Values in bold indicate the best location, sizing and fitness achieved using the proposed approach.

Table 6
The results of optimal DG for 33-bus compared with other algorithms. Two DG without reactive power support: penetration level $\mu > 50\%$.

Methods [22]	Bus *N*	DG size (KW)	Losses (KW)	Loss reduction %
ELF	12	1020.0	87.63	58.51
	30	1020.0		
IA	6	1800.0	91.63	56.61
	14	720.00		
MINLP	13	850.00	87.16	58.69
	30	1150.0		
PSO	12	1000.0	87.50	58.52
	30	1020.0		
Proposed method	**13**	**850.0816**	**85.908**	**57.612**
	30	**1154.2809**		

Values in bold indicate the best location, sizing and fitness achieved using the proposed approach.

Table 7
The results of optimal DG for 33-bus RDS compared with other algorithms. Two DG with reactive power support: penetration level $\mu > 50\%$.

Methods [24]	Bus *N*	DG size (KW)	Losses (KW)	Loss reduction %
IA	6	1800.0	44.84	78.77
	30	900.00		
MINLP	13	819.00	29.31	86.10
	30	1550.00		
PSO	12	818.00	39.10	81.49
	29	1699.00		
Proposed method	**13**	**845.884**	**28.523**	**85.926**
	30	**1114.82**		

Values in bold indicate the best location, sizing and fitness achieved using the proposed approach.

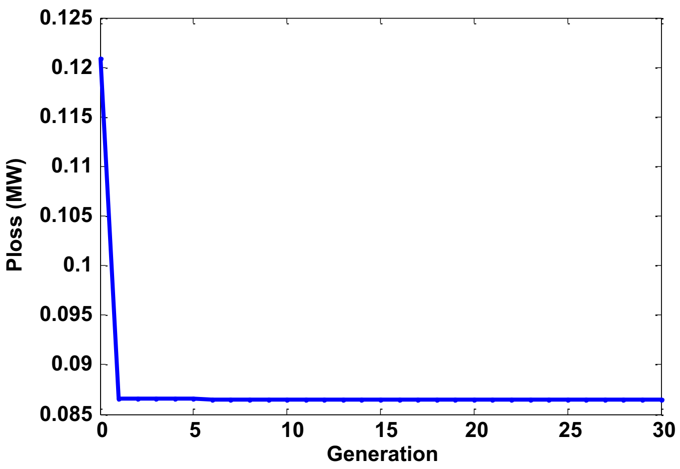

Fig. 17. Convergence characteristic of the power loss minimization: two DG without reactive power support: penetration level $\mu \le 50\%$.

growth. In this scenario, the contribution of SVC device is not considered. Two distributed generations have been installed at the two best locations (13, 30).

In order to investigate the importance of integrating of DG in distribution power system, the system is pushed to a specified critical situation by increasing the active and reactive power at all loads. The following equations describe the relation between load increase and loading margin stability.

$$P_{new} = \lambda \cdot P_{base} \tag{18}$$

$$Q_{new} = \lambda \cdot Q_{base} \tag{19}$$

where P_{new}, P_{base}: the new and basic active power demands; Q_{new}, Q_{base}: the new and basic reactive power demands; λ: loading margin stability.

7.4.1. Case 4: Integration of two DG without reactive power capability

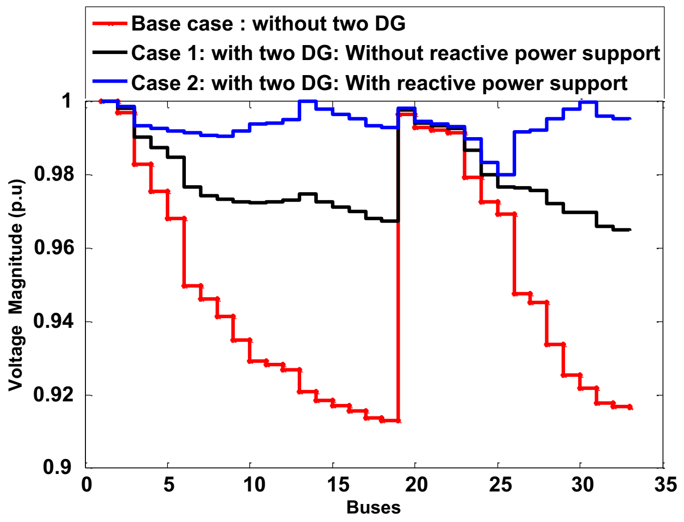

Fig. 18. Voltage profiles comparison: cases: basic case, integration of two DG with and without reactive power support of DG: penetration level $\mu \le 50\%$.

The loading factor taken is 1.5, two DG are located at buses 13 and 30, and two tests are considered. In the first test, the DG has the capacity to exchange reactive power with the network, and in the second test, the DG cannot exchange reactive power with the network. For the first test, the best total power loss achieved is **65.0154** MW, which is better than the total power loss optimized in the second test without considering reactive power support (**200.1753 KW**). The cost of energy loss is reduced from **$260875.39880** to **$34172.1106**, resulting to annual savings of **$226703.2882**. Table 10 shows details of technical and economic results related to the optimal location and sizing of two DGs at specified loading margin stability. The distribution of voltage profiles at all loads as shown in Fig. 19 are within their admissible limits (0.9, 1 p.u.). It is important to note that by considering the reactive power support of the two DG, the total size of DG required to achieve the optimized total power loss is reduced to **2.940** MW compared to the case without considering reactive power support (3.04 MW).

Table 8
The results of optimal DG for 33-bus compared with other algorithms. Two DG with reactive power support: penetration level $\mu \le 50\%$.

Method	Bus *N*	DG size (MW)	Losses (KW)	Loss reduction %
BSOA [23]	13	0.777	31.98	/
	29	1.032		
Proposed method	**13**	**0.801**	**29.267**	**85.56**
	30	**1.056**		

Values in bold indicate the best location, sizing and fitness achieved using the proposed approach.

Table 9
The results of optimal DG for 33-bus compared with other algorithms. Two DG without reactive power support: penetration level $\mu \le 50\%$.

Method	Bus *N*	DG size (MW)	Losses (KW)	Loss reduction %
BSOA [21]	13	0.880	89.34	/
	31	0.924		
Proposed method	**13**	**0.791**	**86.46**	**57.33**
	30	**1.066**		

Values in bold indicate the best location, sizing and fitness achieved using the proposed approach.

7.4.2. Case 5: Integration of two DG with reactive power capability

As shown in Table 10, when the reactive power support of the two DG is considered, a reduction in total DG size to achieve power loss is reduced from 3.04 MW (two DG without reactive power capability) to 2.940 MW (two DG with reactive power capability).

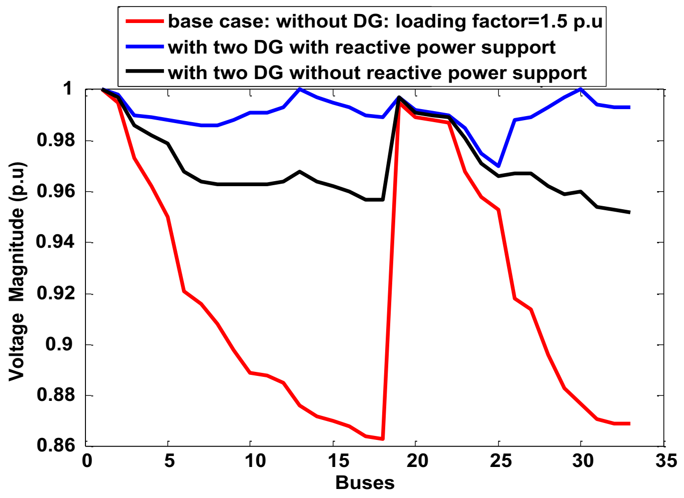

Fig. 19. Voltage profiles comparison: cases: basic case, integration of two DG with and without reactive power support: loading factor = 1.5.

Table 10
Results for 33-Bus: integration of two DG without SVC device: loading factor = **1.5.**

	Without DG	With two DG without reactive power support	With two DG with reactive power support
DG location	–	**13, 30**	**13, 30**
DG size (KVA)	–	**1280, 1760**	**1260,00, 1680,00**
Total active power loss (KW)	496.338	**200.1753**	**65.0154**
Minimum bus voltage (p.u.)	0.8634, bus 18	0.9522, bus33	0.97, bus 25
Pload (kW)	5572.5	5572.5	5572.5
Qload (KVAR)	3450.0	3450.0	3450.0
Cost of PDG ($/h)	0	61.4285	59.3390
Cost of energy losses ($)	260875.39880	105212.17793	34172.1106
Loss reduction %	–	59.66%	86.90%
Savings in cost of energy losses ($)	–	**155663.22087**	**226703.2882**
Total size of DG (MW)		**3.04**	**2.940**

Values in bold indicate the best location, sizing and fitness achieved using the proposed approach.

Table 11
Results of 69 bus system for different algorithms considering only shunt compensation.

Items	Without compensation	With compensation							
Methods [41]		*PSO*	*DSA*	*TLBA*	*F-GA*	*DE-PS*	*Heuristic*	*FPA*	*Proposed ADSA*
Total losses (KW)	224.8949	152.48	147.00	146.35	156.62	146.1347	148.48	150.28	**153.42**
Loss reduction (%)		32.2	34.64	34.92	30.4	35.02	34	33.2	**31.78**
Minimum voltage (p.u.)	0.9092	–	–	0.9313	0.9369	0.9327	0.9305	0.9333	**0.9244**
Optimal location and size in KVAr		46 241	61 900	12 600	59 100	61 950	8 600	61 1350	**61 1221.5**
		47 365	15 450	61 1050	61 700	64 200	58 150	– –	**– –**
		50 1015	60 450	64 150	64 800	59 150	60 1050	– –	**– –**
		– –	– –	– –	– –	65 50	– –	– –	**– –**
		– –	– –	– –	– –	21 300	– –	– –	**– –**
Total KVA		1621	1800	1800	1600	1650	1800	1350	**1221.5**
Annual cost ($/year)		88006.5	85663.2	85321.56	90119.5	86758.4	86441.1	84038.06	**85302.303**

Values in bold indicate the best location, sizing and fitness achieved using the proposed approach.

Fig. 19 compares the voltage profiles of two DG with and without reactive power support using a loading factor of 1.5.

7.5. Test system 2: 69-Bus

In order to validate the efficiency of the proposed approach, it is validated on a medium size radial electric distribution system consisting of 69 Buses. The single line electric distribution system 69-Bus is shown in Fig. 20. This network has a voltage of 12.66 kV, and the required technical data are adopted from Reference 41. The limits of active power of DGs are between 0 and 2 MW. In this section, the effect of the optimal location and sizing of multi SVC devices on power loss reduction is investigated. The maximum reactive power of SVC device to be exchanged with the network is 1500 KVAR. The total loss achieved at normal condition without compensation is 224.7 KW and 102.13 KVAr [41], respectively. The bus voltage limits at all buses are 0.9 p.u. and 1.0 p.u.

Two cases are considered. In case 6, and for fair comparison, we have investigated the effect of reactive power compensation of SVC device installed at bus 61 to reduce the total annual cost. The total annual cost is optimized to $85302.303. As well depicted in Table 11, the value of total cost is better compared to the majority of methods cited except the FPA. The reactive power of SVC device required is 1221.5 KVAr which is lower than other algorithms. In case 7 one DG type solar source is installed at bus 60 in coordination with shunt SVC device installed at bus 61. As shown in Fig. 21, the profile of voltages at all buses improved when considering the integration of one DG (solar source) in coordination with SVC device. The optimal results for three cases: base case, case 6 and case 7 are shown in Table 12.

7.6. Results discussions and practical issues

1. Based on the methodology introduced in this paper and results found, it has been confirmed that it is not always true that the integration of DG with large size results in the increase on system loadability and the improvement of power quality indices.
2. An optimal size of DG must be determined to achieve the optimal power quality indices such as power losses and total voltage deviation. In a smart grid, the optimal active power delivered by multi distributed generation must be optimized dynamically based on network topology, active power demand and considering the presence of SVC device.
3. To achieve the desired power quality indices and to reduce simultaneously the total power losses and the total voltage deviation, there is an optimal reactive power to be exchanged with the network using SVC device in coordination with an

Table 12
Comparison results of 69 bus system: base case, case 6 and case 7.

Optimized values	Base case	Case 6: with SVC	Case 7: with SVC and DG
Total losses (kW)	224.8949	153.42	**33.45**
Loss reduction (%)	–	31.78	**85.13**
Minimum voltage (p.u.)	0.9092	0.9244	**0.9712**
Location of SVC	–	61	**61**
Size of SVC (KVAr)	–	1221.5	**1222.5**
Location of DG	–	–	**60**
Size of DG (KW)	–	–	**1200**

Values in bold indicate the best location, sizing and fitness achieved using the proposed approach.

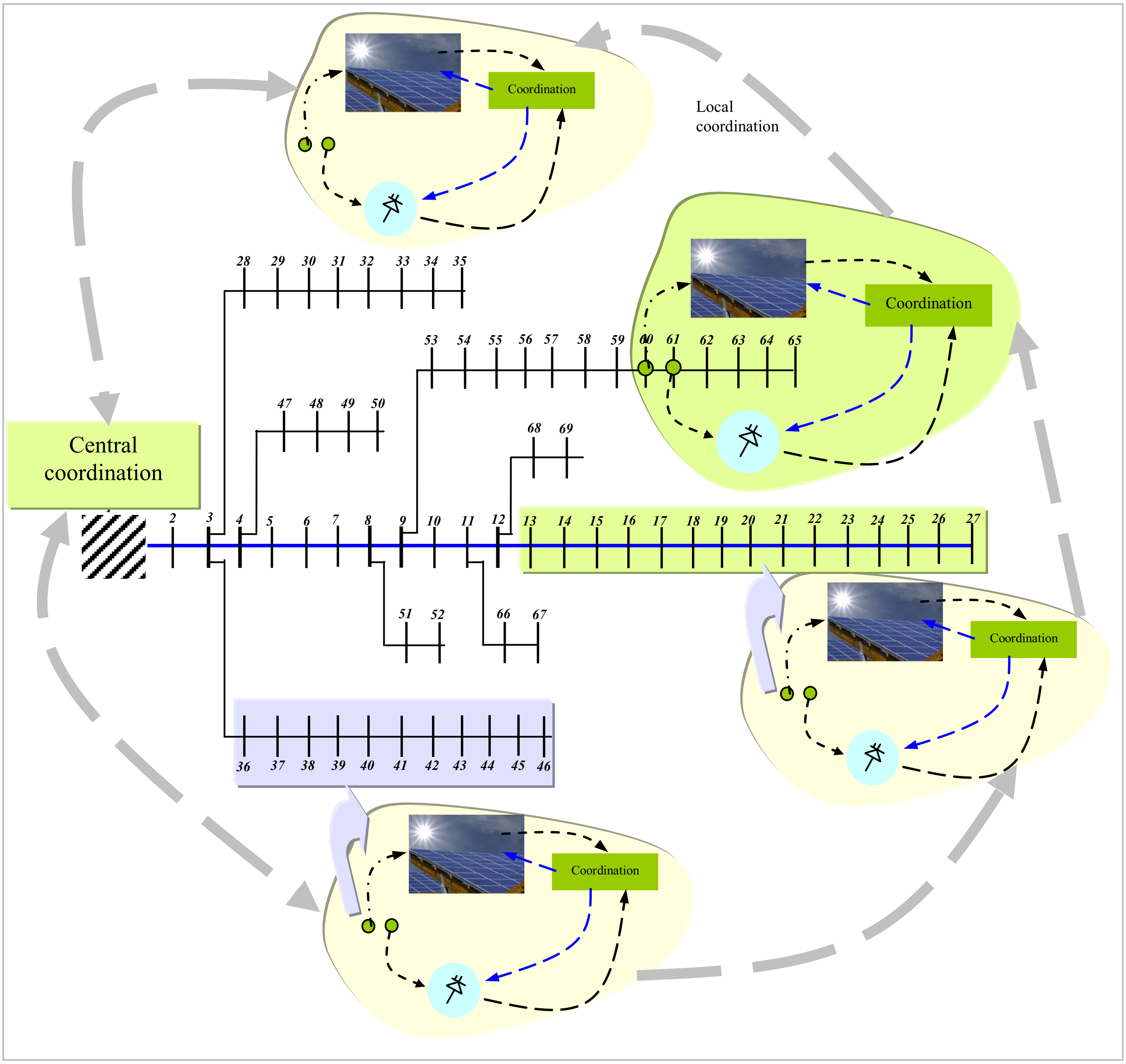

Fig. 20. Modified single line diagram of the 69 Bus electric distribution system with integration of multi DG and multi SVC devices.

optimized DG capacity. This optimized reactive power exchanged with the network depends on the type of DG and the location.

4. In this study two penetration levels are considered (70% and 50%), these two values taken only for comparison with others methods. In practical situation, the penetration level depends on many technical and economic factors based on utilities strategies. In specific situation the main objective function of utilities is related to minimize the penetration level (the size of DG) considering the security limits.
5. As well depicted in Table 10, it is important to conclude that by installing one SVC device at bus 30 considering the DG without reactive power support, the total power loss achieved is 56.8793 MW, which is better compared to the case considering one DG with reactive power support. This particular result proves the importance for solving the problem coordination between different types of DG and SVC devices.
6. Based on results analysis of 69 Bus test system, we can conclude that the SVC is very suitable than conventional shunt compensation due to the following points:
   - 6.1 Power system is dynamic; the flexibility of SVC device allows efficient coordination between different types of DG installed at specified location compared to classical shunt compensators.
   - 6.2 It is important to note that the global optimal location of multi SVC device and DG depends on the global database generated by analysis of distribution test systems considering load growth, faults and provision of extension.

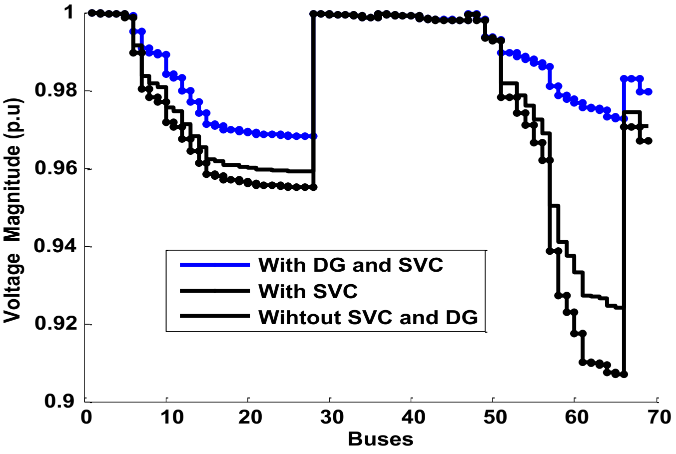

Fig. 21. Voltage profiles comparison: cases: basic case, integration of one DG and one SVC, and with only one SVC.

6.3 The conventional shunt compensation is not suitable for modern distribution systems characterized by the intermittent aspect of various DG.

7. In the future, simultaneous reconfiguration of practical distribution system and allocation of multi types of *dispersed* DG considering their *intermittent* aspect in coordination with multi distributed STATCOM will be treated to improve reliability of modern distribution power system.

8. Conclusion

In this paper, a new variant based differential search algorithm is proposed. The proposed variant named adaptive differential search algorithm (ADS) with dynamic adjustment of control parameters has been implemented and successfully applied to solve the simultaneous optimal location and sizing of multi DG and shunt SVC device for power loss reduction. The particularity and robustness of the proposed planning strategy based DS algorithm in terms of solution quality and convergence behavior is validated on two practical radial distribution systems: 33 Bus and 69 Bus electric networks at normal condition and considering load growth. It is observed from results of different previous scenarios that the proposed optimization strategy is more effective in minimizing the power loss and improving the voltage profile compared to other methods. The flexibility and efficiency of the proposed planning strategy based on DS algorithm will be exploited to study and analyze the optimal location of multi type of DG considering reconfiguration of distribution networks at normal and critical situations.

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